Carbon Back Sputter Modeling for Hall Thruster Testing

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Outline

• Statement of Problem
• Carbon Back Sputter Review
  – Observed Back Sputter
  – Sputter Yields
  – Sputter Models
• Current Work
  – Model Approach
    ▪ Analytic
    ▪ Numerical
      o HAP
    ▪ Experiment
  – Results
    ▪ Modeling
    ▪ Experiment
  – Conclusions
Facility Back Sputter Affects on Thruster Life Validation

- Carbon sputtering from vacuum facility walls introduces contamination and deposition back to thruster surfaces
- As space based erosion mechanisms are progressively reduced, facility deposition effects become more important.
  - NEXT Ion thruster grid life (51.2 kh Extended Life Test)
  - Magnetically Shielded Hall Thruster insulator life (50 kh design life)
- Possible effects of back sputter on life testing
  - Competitive deposition/erosion processes on insulator surfaces could mask erosion process in space
  - Build up of conductive carbon layers could introduce arcing or shorting in ground test thrusters
Tests with facility carbon observed

- Previous life and wear tests have experienced facility back sputter
- Ion
  - NSTAR Extended Life Test (~30,000 h/150 kg throughput)
    - Net erosion observed on grid
  - NEXT 2000 h wear test
  - NEXT Long Duration Test (51,200 h/918 kg)
    - Carbon lined chamber
    - QCM measurement
    - Carbon deposition at localized positions on grid
- Hall
  - SPT-100 (90’s)
    - Low accuracy – visual observance of films on back of witness plates
  - H6 Magnetic Shield Testing (100’s of h)
    - QCM measurement at single location near thruster
    - BN surface profiles
  - HERMeS Thruster (on going)
# Summary of Carbon/Life Tests

<table>
<thead>
<tr>
<th>Thruster</th>
<th>Tank</th>
<th>L (m), D(m)</th>
<th>$\lambda$</th>
<th>$n$</th>
<th>Specific Impulse (sec)</th>
<th>Beam Voltage (V)</th>
<th>Beam Current (A)</th>
<th>Measured Carbon Deposition ($\mu$m/khr)</th>
<th>Predicted ($\mu$m/khr)</th>
<th>Measured as % of Predicted</th>
<th>Normal Sputter Yield Atoms/ion</th>
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<tbody>
<tr>
<td>NSTAR ELT, wear test</td>
<td>JPL 148</td>
<td>10, 3</td>
<td>64</td>
<td>0.94</td>
<td>2000-3000</td>
<td>650-1100</td>
<td></td>
<td>14-20 / 0.7</td>
<td>18 / 0.6</td>
<td>78-110</td>
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<td>NEXT 2khr</td>
<td>GRC VF 6</td>
<td>21, 7.3</td>
<td>64</td>
<td>0.94</td>
<td>4000</td>
<td>1800</td>
<td>3.52</td>
<td>2</td>
<td>0.56</td>
<td>360</td>
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<td>NEXT LDT c. 2005</td>
<td>GRC VF 16</td>
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<td>64</td>
<td>0.94</td>
<td>4000</td>
<td>1800</td>
<td>3.52</td>
<td>3.02</td>
<td>3.94</td>
<td>77</td>
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<td>HiPEP (Herakles Precursor) 2khr</td>
<td>GRC VF 6</td>
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<td>7440</td>
<td>5500</td>
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<td>7080</td>
<td>4809</td>
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<td>7.2-7.8</td>
<td>9.78$^\dagger$</td>
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<td>5</td>
<td>3-10</td>
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<td>T6</td>
<td>IV10</td>
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<td></td>
<td>4632</td>
<td>~2700</td>
<td>4.5</td>
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<td>MS Hall</td>
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<td></td>
<td></td>
<td>4632</td>
<td>2000</td>
<td>300</td>
<td>20</td>
<td>4</td>
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<td></td>
<td>3000</td>
<td>800</td>
<td>11</td>
<td>2.5</td>
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<td>SPT-100</td>
<td>VF-5</td>
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<td>2500</td>
<td>300</td>
<td>4.5</td>
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</table>


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Chart 5
HERMeS Back Sputter Modeling Approach
In Parallel:

- Adapt analytic approach (Van Noord, Soulas, Reynolds) to Hall thruster plume
  - Add empirical $j(\theta)$, $E(\theta)$ description for more divergent Hall thruster plume
  - Apply to VF-5 (cylindrical) geometry

- Detailed numerical model of full VF-5 geometry, HERMeS Plume
  - HAP DSMC code to track Xe plume, model carbon sputtering particle distribution, and track carbon flux to thruster plane.
  - HAP already used to model pumping speeds in VF-5 with actual cryopanel geometry
Analytic Model

• Ray tracing/Free Molecular Flow
• Axisymmetric
• Trace thruster plume flow to walls
  – Line of site plume propagation to walls
    ▪ $j(\theta) \Rightarrow j(r,z)$
  – Angle of incidence from geometry
    ▪ $(\beta) \Rightarrow \beta(r,z)$
  – Calculate yield of sputtered particles production to emission angle $\alpha(r,z)$
    ▪ $Y(E_i, \beta, \alpha) = Y_0(E_i) f(\beta) \cos(\alpha)/\pi$
  – Track flux of particles back to thruster plane through view factors
Analytic Model

- **Input profiles**
  - Plume data obtained from HERMeS probe measurements
    - *Faraday, Langmuir, EXB probes*
  - Using a quasi-analytic approach – spline fit $j(\theta)$, $E(\theta)$ data instead of a single function curve fit

- **300 V, 9.4 kW**
  - Log$_{10}$(Current Density)
  - Energies

- **600 V, 12.5 kW**
  - Log$_{10}$(Current Density)
  - Energies
Sputter Yield Model

- Total number of particles sputtered determined by incident energy (E) and angle (β)
  - Empirical fit to data
  
  \[ Y(E, \beta) = 4.123 \times 10^{-5} E^{1.388} e^{-1.0556(-1 + \sec(\beta))} \cos(\beta)^{3.427} \]

- Defines total number of particles produced, not the direction of the sputtered atoms
- For HAP, assumed a constant sputtered particle energy of 3 eV

![Graph of Normal Sputter Yield](image)

![Graph of Angle of Incidence Yield](image)
Hypersonic Aerothermodynamics Particle (HAP) Code

• Direct Simulation Monte Carlo Code developed for hypersonic applications
  – Previously used to predict pumping performance in NASA GRC VF-5
  – Thruster plume is defined on a 1 m radius, ¼ spherical surface
    ▪ Data obtained from HERMeS probe measurements
    ▪ Faraday, Langmuir, EXB probes
  – Variable Hard Sphere energy-dependent cross sections
    ▪ Xe: \( d_{ref} = 5.74 \text{ Å}, \omega = 0.35 \)
    ▪ C: \( d_{ref} = 3.23 \text{ Å} \)
    ▪ \( T_{ref} = 273K \)
Vacuum Facility 5 geometry for HAP

- Half of chamber simulated due to symmetry
- Thruster is located 0.1 m below center line
- Cryo pump surfaces included
- End beam dump made of angled carbon plates
  - 10° upper plates to the vertical upper plates, 30° lower plates
- All surfaces assumed carbon coated
- Plume inflow defined over ¼ sphere at 1 m radius
- Calculations within flux surface (at thruster) not accurate
Experimental Measurements

- Ongoing wear testing of HERMeS TDU-1 thruster
  - Wear operating condition: 600 V, 12.5 kW
  - Testing has exceeded 1000 hours
- As part of testing, 3 Quartz Crystal Microbalances located near thruster plane
- Back sputter deposition measured continuously during testing
RESULTS
• **Total deposition at thruster**
  - 0.3 µm/kh (300 V)
  - 1.1 µm/kh (600 V) at thruster
• **Uniform (<10%) across thruster plane**
• **Relative contributions of walls and end cap dependent on power, energy, plume shape**
• 300 V case shows sputter from walls near thruster
  – Wall sputter from 2 – 6 m
  – End Cap sputter at 0.5-1.0 m radius
• 600 V case wall sputter occurs further from thruster
  – Wall sputter from 2 – 6 m
  – End Cap sputter at 0.2-0.5 m radius
HAP Calculation
Axial Carbon Flux Back to Thruster

- Incorporates diffuse sputter directional distribution
- Over estimates flux magnitude
- Calculate axial flux at a plane 0.1 m in front of input boundary
Calculated Sputter Deposition Profile 1.1 m from Thruster Plane

- Deposition thickness rate across plane in front of the center
  - Calculated from axial flux across the plane
  - Top/bottom asymmetry from beam dump, thruster location
  - Uniformity across symmetry axes is comparable to measurement, analysis.

- Much higher rates than measured
  - Cause under investigation
  - Plume data is the same as that used in analytic model
  - Yield calculation, particle propagation still being investigated
Experimental Measurements

• Primary wear test point: 600 V, 12.5 kWe

• During wear test, the thruster was tested with two pole cover materials:
  – Graphite
  – Alumina

<table>
<thead>
<tr>
<th>Pole Cover</th>
<th>QCM 1 (µm/kh)</th>
<th>QCM 2 (µm/kh)</th>
<th>QCM 3 (µm/kh)</th>
<th>Analytic Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphite</td>
<td>1.74</td>
<td>1.90</td>
<td>1.81</td>
<td>1.1 µm/kh</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>1.55</td>
<td>1.67</td>
<td>1.63</td>
<td></td>
</tr>
</tbody>
</table>

• Measurements are 1.6 – 1.8 µm/kh, higher than analytic prediction
Conclusions

- To support life validation of high power Hall thrusters such as the HERMeS thruster, analytic and DSMC models of carbon back sputter in the NASA GRC VF-5 facility have been developed.
  - Both models incorporate empirical Hall thruster plume profiles
  - Empirical sputter yields, distributions are used

- Model predictions are benchmarked with experimentally measured deposition rates in the HERMeS wear test

- At the HERMeS thruster wear test operating condition, 600 V and 12.5 kW:
  - Analytic model predicts 1.1 µm/kh
  - Measurements give 1.5 – 1.8 µm/kh

- Modeling is being benchmarked with back sputter measurements in the ongoing HERMeS thruster wear test
  - Analytic model under-predicts deposition by 50%
  - DSMC code gives unrealistically high deposition rates
Future Work

- Resolve DSMC over-prediction
  - Generate test cases to evaluate accuracy
  - Refine inflow boundary (extends computational time)
- Examine model sensitivity to plume profiles
- Improve differential sputter yield relation to include both polar and azimuthal dependence of sputtered material
- Continue gathering experimental back sputter data for remainder of HERMeS wear test